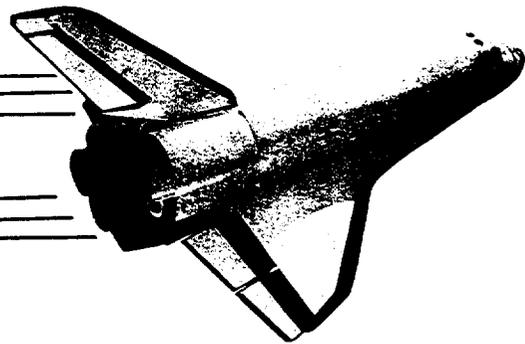


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LUBRICATION OF SPACE SYSTEMS[®]

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NASA has many high technology programs planned for the future: such as the space station, "Mission to Planet Earth" (a series of Earth observing satellites), space telescopes, and planetary orbiters and landers. These missions will involve advanced mechanical moving components that will need wear protection and lubrication. The tribology practices used in space today are primarily based upon a technology more than 20 years old. The question is, is this technology base good enough to meet the needs of these future long-duration NASA missions? This paper examines NASA's future space missions, how mechanisms are currently lubricated, some of the mechanism and tribology challenges that may be encountered in future missions, and some potential solutions to these future challenges.

INTRODUCTION

The space age brought with it many lubrication challenges that had not been experienced in the past: exposure to very low ambient pressures, a radiation and atomic oxygen environment, the presence of meteoroids, the absence of a gravitational field, imposed weight limitations, contamination by vapors, and the use of mechanical components that were not maintainable.

The challenges for future spacecraft appear to be even greater because missions are being planned that will require mechanisms to last for much longer periods of time. For example, it is desired to have a maintenance-free life for the space station of 30 years. This will be extremely hard to accomplish because most mechanisms do not last that long on Earth without maintenance. The only mechanism with a 30 year maintenance-free life that comes to mind is a refrigerator compressor.

In addition to Earth orbiting spacecraft, Lunar missions are being planned that will require mechanical systems capable of operating over a temperature range of -181°C to $+111^{\circ}\text{C}$, in a vacuum of 10^{-12} torr, and under extremely dusty conditions. Missions are also being planned for the planet Mars where there is a predominately carbon dioxide atmosphere, a dusty corrosive soil, high winds, and a wide range of temperatures.

This paper will discuss some of NASA's proposed future missions and then discuss some of the tribological problems that will be encountered. Lubrication techniques that have been used in the past will be described and their advantages and disadvantages will be discussed

FUTURE NASA SPACE MISSIONS

Currently, NASA missions can be broken down into five major areas.

1. Planetary Exploration—Explore and understand evolution of planetary bodies.
2. Mission to Planet Earth—Understand the interaction between oceans, atmosphere and land (weather); living organisms and the environment; the environment and pollution; and the composition and evolution of the Earth.
3. Astrophysics—Understand the universe (laws of physics, birth of stars and planets, and advent of life).
4. Material and Life Sciences—Understand and develop new processes (fluid dynamics, combustion fundamentals, material processing, physics and chemistry, and space medicines).
5. Communications—Develop new space communications systems required to meet the expanding needs of U.S. industry and government agencies.

Figure 1 shows a proposed time frame for completion of some of the hardware that will be needed to complete some of these missions. The figure separates the hardware classes into transportation, spacecraft, and large space systems. The figure is somewhat out of date because the Clinton administration has dropped President Bush's "Space Exploration Initiative" which was a long-range, continuing commitment for human space exploration. President Bush proposed landing men and women on Mars by 2019.

Planetary Exploration

As mentioned previously, the Space Exploration Initiative has been discontinued. This mission would have used the space station as base for expanding human presence to the Moon and Mars. Vehicles like the one shown in Fig. 2, a nuclear powered rocket, would have been assembled to transport humans to Mars. The vehicle would have had

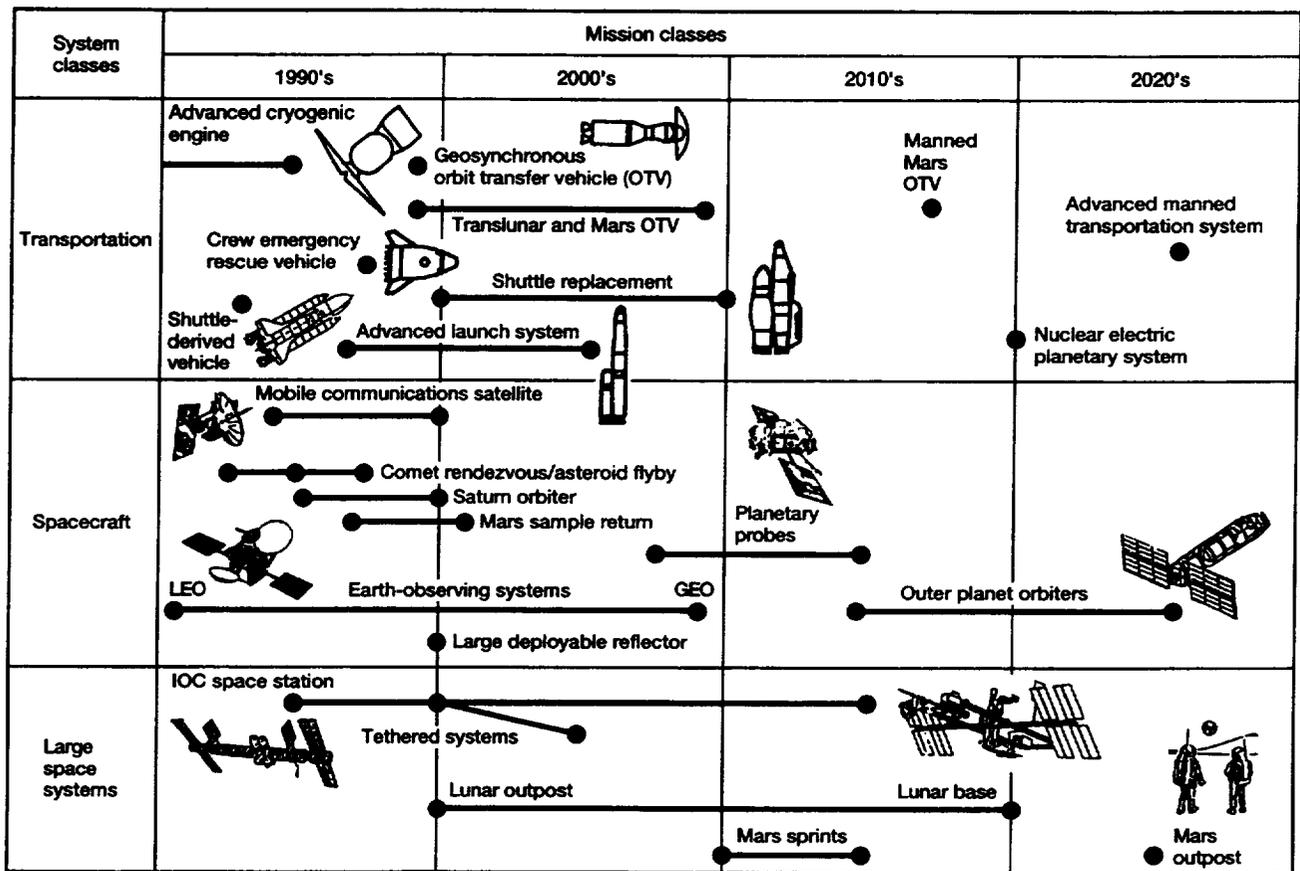


Fig. 1 - Proposed time frame for future NASA missions.

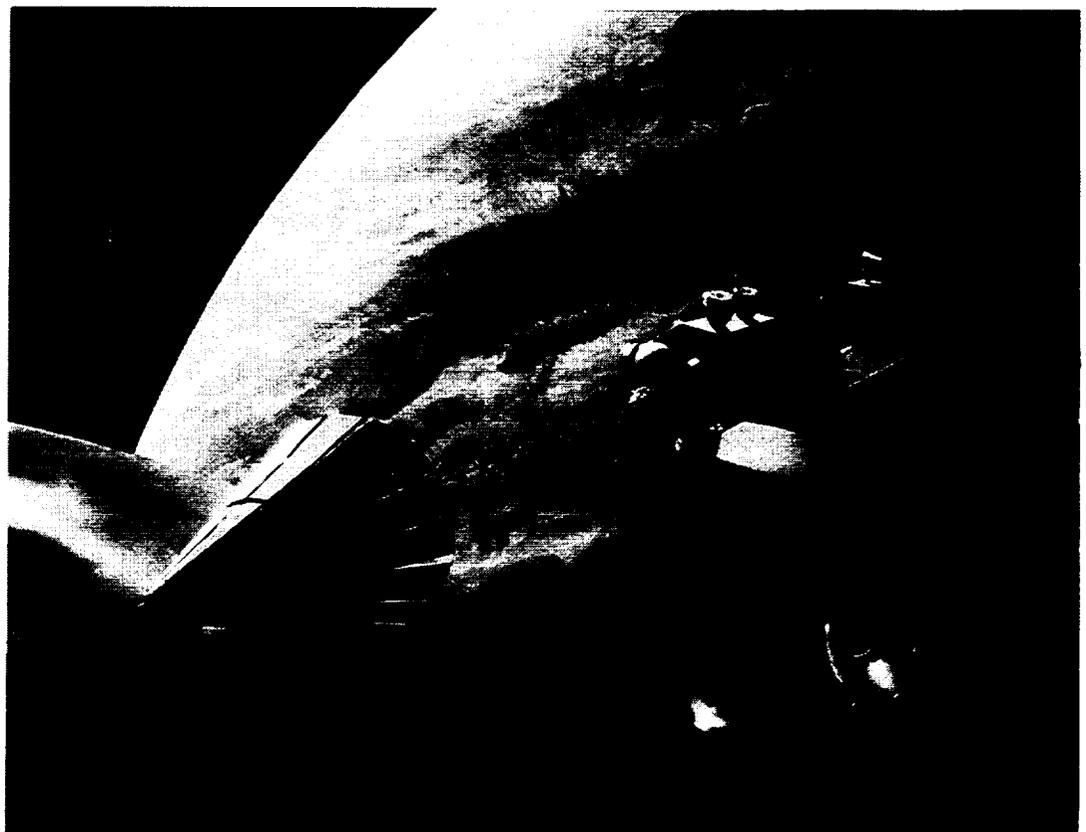


Fig. 2 - Nuclear powered rocket.

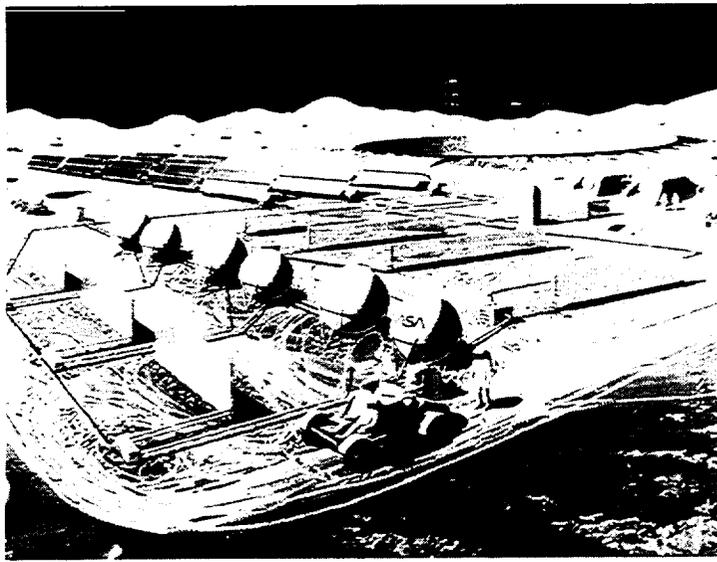


Fig. 3 - Future Lunar community.

three sections, a nuclear rocket section, crew section and a section consisting of an aerobrake, which would have been used for reducing the speed of the vehicle.

The moon would have been used as a training base for the astronauts before they were to be sent to Mars. Self sufficient communities would be built which would process the lunar soil to supply oxygen, hydrogen, and water. Since it would take much less energy to get to the space station from the moon than from the Earth, water and fuel would be supplied to the space station from the moon. Figure 3 shows an artist's conception of what a possible lunar community may have looked like.

While human planetary missions are currently not in the near range plans, NASA is planning to conduct robotic missions to Mars. MESUR Pathfinder, an autonomous robotic system, is being designed to be launched to Mars before the end of the decade. Figure 4 shows an artist rendition of what such a robot might look like.

Mission to Planet Earth

NASA, other Federal agencies and some foreign governments have been developing plans to bring about a better understanding of what is happening to our planet on a global scale. In the next century, planet Earth faces the potential hazard of rapid environmental change, including climate warming, rising sea level, deforestation, desertification, ozone depletion, acid rain and reduction of biodiversity. Such changes could have a profound impact on human life. In order to prevent a potential deleterious effect on human life, data must be collected to understand the processes taking place so that we can take steps, if need be, to counteract these negative effects. A series of satellites called EOS (Earth Observing System) have been planned so that data can be taken to study these effects.

The first of the EOS observatories is scheduled to be launched in June 1998. It has been designated EOS-AM-1 and will carry five instruments which will characterize terrestrial and oceanic surfaces, examine clouds and aerosols, determine the radiation reaching and emanating from the Earth and determine the overall radiative energy balance of the planet.

In addition to EOS some other atmospheric satellites have been launched or planned to be launched. The upper atmosphere Research Satellite (UARS) was launched in September 1991 to better understand the processes at work in the upper atmosphere region of the Earth environment. It provides the first comprehensive data on chemistry, wind velocities and energetics of the Earth's upper atmosphere. The Tropical Rainfall Measuring Mission (TRMM) is a joint venture with Japan and is slated to be launched in 1997. It will collect data to improve the knowledge of tropic rainfall, it's distribution and variability, it's effect on global energy and water cycle, and to improve models for the prediction of global circulation and rainfall variability. It will also study cloud distribution, lightning, and radiant energy's effect on the Earth.

NASA also builds and launches satellites for the National Oceanic and Atmospheric Administration (NOAA). The Television Infrared Operational Satellites (TIROS) were designed to transmit data directly to users around the world for weather analysis. The Geostationary Operational Environmental Satellites (GOES) constantly monitor atmospheric effects for radio and television weather forecasts.

Astrophysics Missions

A number of Satellites have been launched in Earth orbit to study the solar system as well as the rest of the universe. The Hubble Space Telescope (HST) is the most well-known, launched in April 1990. Also in orbit is the Compton Gamma Ray Observatory (Compton), launched in April 1991. This observatory scans the heavens in search of gamma-ray evidence of the most energetic phenomena in the universe such as solar flares, super novae, pulsars, quasars, black holes, and galactic structures. The International Solar Terrestrial Physics Program (ISTP) is scheduled to be launched in 1996. It's purpose is to study the interactions in the Sun-Earth system. NASA, ESA and Japan are collaborating in this effort. The Extreme Ultraviolet Explorer (EUVE) was launched in June 1992. It's mission is to determine the distribution of extreme ultraviolet sources within and outside the Milky Way and to investigate their physical properties and chemical compositions. The Far Ultraviolet Spectroscopic Explorer (FUSE) is planned to be launched in the year 2000. It will investigate the processes of star formation and the development of the

Fig. 4 - Martian planetary robot.



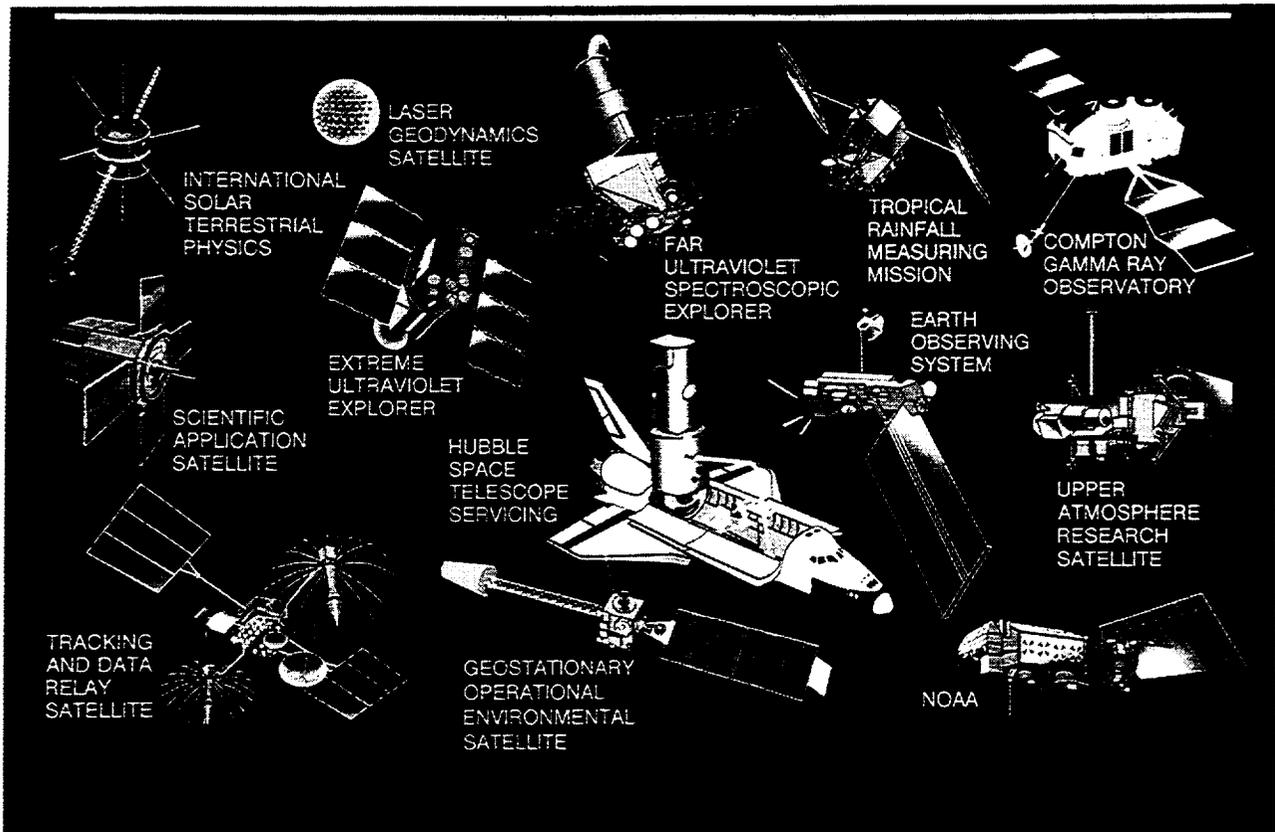


Fig. 5 - Earth orbiting NASA satellites.

early universe. It may be able to tell scientists about the origin and evolution of stars and solar systems. Figure 5 depicts many of the Earth orbiting satellites that NASA has launched or intends to launch.

In addition to satellites launched into Earth orbit, NASA has launched many satellites to orbit or flyby other bodies within the solar systems. Galileo is currently on it's way to Jupiter to study that planet and just recently sent back photos of the collision of a comet with Saturn. A mission to study Saturn and Saturn's moons is being planned. The mission is called Cassini and the planned launch date is 1996. A mission to Pluto, called the Pluto Fast Flyby is also being planned. Pluto will be at it's closest approach to Earth in about 12 years and is in ideal position for such a mission. Another Mars Observer Spacecraft is being planned, but the date of when it will be launched is uncertain.

Material and Life Sciences Missions

These type of experiments are currently conducted on the space shuttle. In the future, more extensive experiments will be able to be conducted on the space station. The latest version of the space station will be an international effort with the Russians participating as full partners with the United States along with the Europeans and the Japanese. Hopefully, experimenting in space will lead to the development of advanced new materials and medicines for the betterment of mankind. Figure 6 gives an artist rendition of the present design of the space station which has been designated Alpha.

Communications Missions

As the nation moves into the 21st century, new space communications systems will be required to meet the expanding demand for communication services. Today's space communication systems evolved from high-risk technology developed from NASA via the Synchronous Communications Satellite (SYNCOM), the Applications Technology Satellite (ATS) and the Communications Technology Satellite (CTS). Space communications systems in the fu-

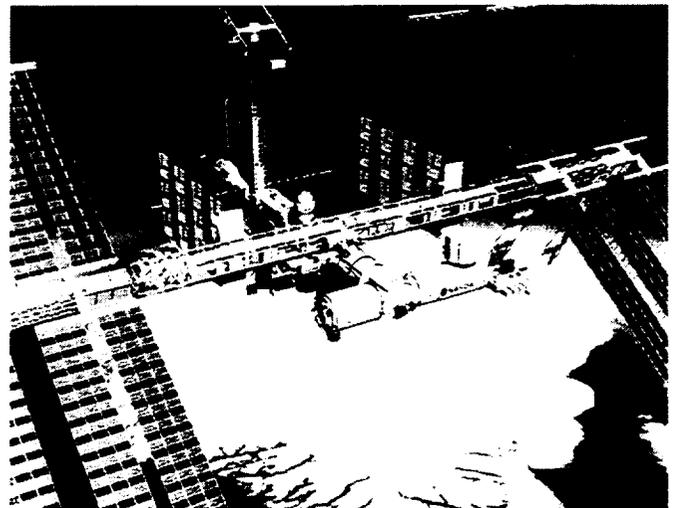


Fig. 6 - Alpha Space Station.



Fig. 7 - Advanced communications technology satellite (ACTS).

ture will require further revolutionary advances in technology to permit more efficient use of orbit and spectrum resources and to allow for new forms of information transfer. NASA is currently experimenting with the Advanced Communications Technology Satellite (ACTS) to respond to these challenges. ACTS is pioneering new high risk technologies that will play an important role in the nation's technological and economic future. Figure 7 gives an artist's sketch of ACTS in synchronous orbit over the Western Hemisphere.

NEED FOR IMPROVED LUBRICATION TECHNOLOGY

To determine if the state-of-the-art space mechanisms are adequate to meet the requirements of future NASA missions, a questionnaire was sent to industry and government personnel known to be working in the field. Unedited responses to the questionnaire are reported in (1). An analysis of the responses is reported in (2). The respondents answered a number of questions assessing current or anticipated needs. Approximately 98% stated that new or improved mechanical component and lubrication technology will be needed for future space missions. The complexity of the tribology problem is indicated in Fig. 8, where the spectrum of operating speeds for future space mechanisms is shown.

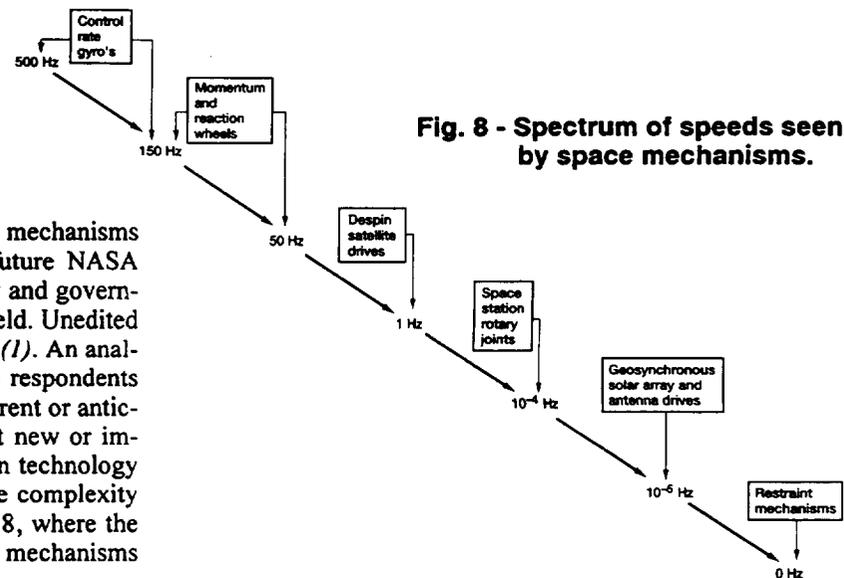


Fig. 8 - Spectrum of speeds seen by space mechanisms.

METHODS USED TO LUBRICATE SPACE SYSTEMS

Liquids

Many different liquid lubricants have been used in space: silicones, mineral oils, perfluoropolyalkylethers (PFPAE), polyalphaolefins, polyolesters, and multiply-alkylated cyclopentanes. Table 1 lists some commonly used liquid space lubricants and their properties. For more details on these lubricants see (3-9).

Because excessive weight is a problem for satellites, large reservoirs of liquid lubricant and the resultant pumping systems (as used in aeronautical applications) are not appropriate. Instead, rolling-element bearings are lubricated with small liquid reservoirs and/or porous cages. The cages are impregnated with lubricant before assembly.

Lubricant can be lost through vaporization, creep, or inadequate supply. To counteract vaporization, low-vapor-pressure fluids, such as the PFPAE's, are used and labyrinth seals are employed. To counteract creep, barrier films are used, for example, in the lands of the races, to prevent the lubricant from creeping into undesirable places. To ensure adequate lubricant supply, positive feed systems have been developed to meter and control the flow of lubricant to the contact areas (10). Wick lubrication has also been proposed as a means of increasing the lubricant supply (11).

Greases

A grease is a semisolid liquid that consists of a liquid lubricant mixed with a thickener. The oil does the lubricating while the thickener holds the oil in place and provides a resistance to flow. Thickeners used consist of soaps (a metallic element such as lithium, calcium, sodium, or aluminum reacted with a fat or a fatty acid) or fine particles of a lubricating additive, such as polytetrafluoroethylene (PTFE) or lead. The consistency of grease varies: it may be so hard that it must be cut with a knife or soft enough to flow under low pressures. As in oils, additives are often added to greases to improve load-carrying ability, oxidation resistance, and corrosion control.

Type of lubricant	Average molecular weight	Viscosity at 20°C, cSt	Viscosity index	Pour point, °C	Vapor Pressure, Pa	
					At 20°C	At 100°C
KG—80, mineral oil		520	101	-9	1x10 ⁻⁶	
Apiezon C, mineral oil	574	250		-15	5x10 ⁻⁷	
BP 110, mineral oil		120	108	-24	5x10 ⁻⁷	
BP 135, ester		55	128	-45	1x10 ⁻⁶	
Nye 179, polyalphaolefin		*30	139	<-60	9x10 ⁻⁷	
Nye UC7, neopentylpolyolester		75		-56	7x10 ⁻⁷	
Nye UC4, neopentylpolyolester		44			3x10 ⁻⁶	
SiHC ₁ , silahydrocarbon, type 1	1,480	278	125	-50		
SiHC ₂ , silahydrocarbon, type 2	1,704	480	128	-15		
Fomblin, PFPAE (Bray 815Z)	9,500	255	355	-66	4x10 ⁻¹⁰	1x10 ⁻⁴
Krytox, PFPAE	11,000	2,717		-15	4x10 ⁻¹²	1x10 ⁻⁷
Demnum, PFPAE	8,400	500±25	210	-53	7x10 ⁻⁹	1x10 ⁻⁵

*Viscosity at 40°C.

Greases are used for a variety of space applications: low-to high-speed, angular-contact ball bearings; journal bearings; and gears. The primary reason for using a grease is that the grease can act as a reservoir for supplying oil to contacting surfaces. It can also act as a physical barrier to prevent oil loss by creep or by centrifugal forces. Greases used for various space applications are described by McMurtrey (3-4).

Solids

Solid lubricants are used in space to lubricate various mechanical components, such as rolling-element bearings, journal bearings, gears, bushings, electrical sliding contacts, clamps and latches, bolts, seals, rotating nuts, robotic and telescoping joints, backup bearings for gas and magnetic bearings, fluid transfer joints, various release mechanisms, valves, and harmonic drives. The following types of solid lubricants are used for these space applications:

1. Soft metal films: gold, silver, lead, indium, and barium.
2. Lamellar solids: molybdenum disulfide, tungsten disulfide, cadmium iodide, lead iodide, molybdenum diselenide, intercalated graphite, fluorinated graphite, and thalocyanines.
3. Polymers: PTFE, polyimides, fluorinated ethylene-propylene, ultra-high-molecular weight polyethylene, polyether ether ketone, polyacetal, and phenolic and epoxy resins.
4. Other low-shear-strength materials: fluorides of calcium, lithium, barium, and rare earths; sulfides of bismuth

and cadmium; and oxides of lead, cadmium, cobalt, and zinc.

The most common way to utilize a solid lubricant is to apply it to a metal surface as a film or coating. Typically, films are used only where it is not convenient or not possible to use a liquid or a grease. Since films have finite lives, they are typically not used for rolling-element bearing applications that would experience more than a million cycles of sliding.

There are many methods of depositing solid lubricant films onto a surface. The easiest method is to rub or burnish powders onto a roughened metallic surface. The next simplest method is to incorporate solid lubricant powders into a liquid binder system; brush, dip, or spray the mixture (much like a paint) onto the surface; and then thermally remove the liquid. More modern techniques include vacuum deposition methods, such as sputtering and ion plating. For more details on application techniques, see (12).

Solid lubricants can also be employed as a solid body, typically in the form of a composite. A composite consists of a matrix material (to provide structural strength) and a solid lubricant material (to provide lubrication). Some polymer materials, such as the polyimides, have demonstrated that they can provide very low friction and wear properties by themselves without being made into a composite (13).

Rolling-element bearings are sometimes lubricated by making the retainer out of a composite lubricant material so that the lubricant can be transferred to the rolling balls and then to the inner and outer races. Figure 9 demonstrates how this film-transfer mechanism operates (14).

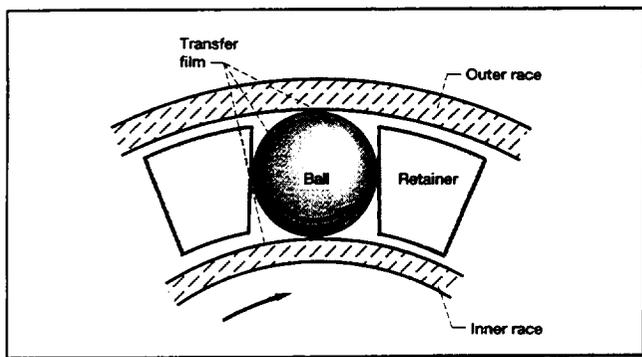


Fig. 9 - Illustration of ball bearing film-transfer mechanism (14).

Generally, this form of lubrication is successful only under lightly loaded conditions; however, the technique has been used with limited success to lubricate the ball bearings in the space shuttle turbopumps.

COMPARISON OF LIQUID AND SOLID LUBRICATION MECHANISMS

Liquid Lubrication Mechanisms

There are four defined regimes of liquid lubrication: hydrodynamic, elastohydrodynamic, boundary, and mixed. These regimes are directly proportional to the oil viscosity Z and to the relative velocity V and inversely proportional to the load L . Figure 10, known as the Stribeck-Hersey curve (15-17), depicts these regimes in terms of coefficient of friction versus the parameter viscosity, velocity, and load (ZV/L).

The first regime is known as hydrodynamic lubrication. This regime is characterized by the complete separation of the surfaces by a fluid film that is developed by the flow of a fluid through the contact region. Typically, the thickness of the lubricant film separating the surfaces is greater than $0.25 \mu\text{m}$ (10^{-5} in.).

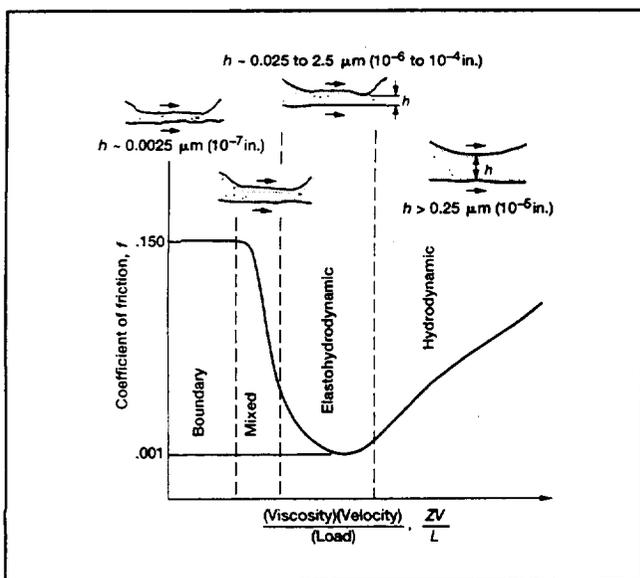


Fig. 10 - Coefficient of friction as function of viscosity-velocity-load parameter [Stribeck-Hersey curve (15-17)].

For nonconformal concentrated contacts, where loads are high enough to cause elastic deformation of the surfaces but speed and viscosity are not large enough to produce film thicknesses greater than $0.25 \mu\text{m}$ (10^{-5} in.), the second lubrication regime comes into effect. This regime is known as elastohydrodynamic lubrication. The thickness of the lubricant film in this regime is $2.5 \mu\text{m}$ (10^{-4} in.) to $0.025 \mu\text{m}$ (10^{-6} in.). Usually, during hydrodynamic and elastohydrodynamic lubrication, no wear takes place because there is no contact between the sliding surfaces.

As the thickness of the oil film decreases to values below $0.0025 \mu\text{m}$ (10^{-7} in.), the boundary lubrication regime comes into play. In this regime, asperity contact between the sliding surfaces takes place, and the lubrication process becomes the shear of chemical compounds on the surface. This regime is dependent on lubricant additives within the oil that produce compounds on the surface which have the ability to shear and provide lubrication. Boundary lubrication is highly complex, involving surface topography, physical and chemical adsorption, corrosion, catalysis, and reaction kinetics. The transition between elastohydrodynamic and boundary lubrication is not sharp, and there exists a region, called the mixed lubrication regime, which consists of some elastohydrodynamic and some boundary lubrication.

Other Factors Affecting Liquid Lubrication

Many factors influence liquid lubrication besides viscosity, speed, and load. Probably the most influential parameter is temperature. Temperature affects the viscosity of oil, which vaporizes at some high temperature or becomes too thick to flow freely at some low temperature. Because oils tend to oxidize, oxidation inhibitors must be added. Sometimes oils contain certain chemicals that corrode metallic surfaces. In some cases the bearing surfaces themselves can initiate the chemical breakdown or polymerization of oils (especially fluorocarbon oils (18-20)). Oils can attack seals and cause them to shrink or swell, and sometimes oils have a tendency to foam, which can cause lubricant starvation.

Thus, in addition to adding chemicals to oils to make them better boundary lubricants, many other types of chemicals must be added to make oils effective lubricants. For more information on the theory of lubrication and the types of additives needed in oils, see Booser (21).

Solid Lubrication Mechanisms

Solid lubrication is essentially the same as boundary lubrication (with liquids), except that there is no liquid carrier to resupply a solid material (such as a chemical reactant) to the surfaces to produce a lubricating solid film. Instead, a solid film must be applied to the sliding surfaces before sliding commences, and this film must last for the life of the component. An alternative to using a film is to make a part of the bearing (e.g., the bearing cage) out of a solid lubricant material or a solid lubricant composite material.

When using films or coatings, two basic lubrication mechanisms must be considered (22). The first mechanism is illustrated in Fig. 11 (22) where a metallic pin is sliding against a film applied to a sandblasted disk. This mechanism is applicable to thin film lubrication where loads are very high. The mechanism involves the shear of an extremely thin layer of solid lubricant (usually less than $2 \mu\text{m}$ thick) between a transfer film on the counterface sur-

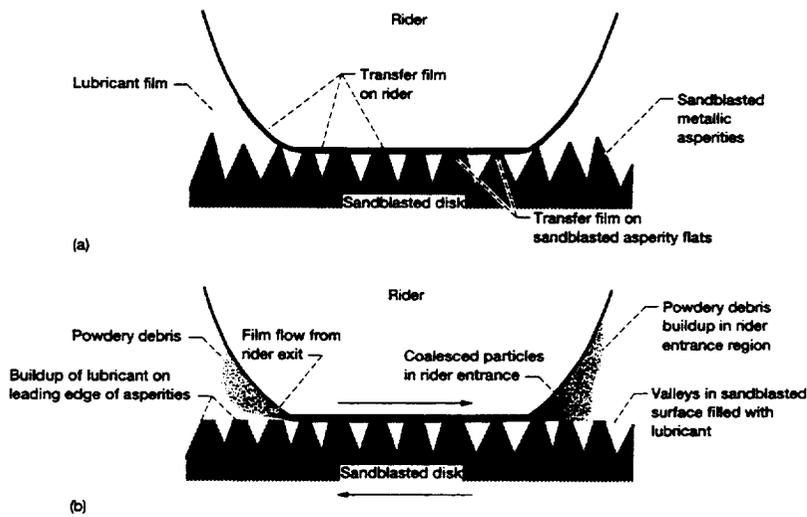


Fig. 11 - Idealized schematic drawing of sliding surfaces illustrating the thin film lubricating mechanisms (12).

face (pin or rider in pin-on-disk testing) and the film itself on the substrate surface. The lubrication process is dynamic. Lubricant builds up in the entrance area of the pin and flows across the pin contact area and out the exit area of the pin. Flow also takes place on the substrate surface (disk in pin-on-disk testing). Having a rough substrate surface is helpful for two reasons: (1) It helps prevent lateral flow of solid lubricant from the contact area, and (2) the valleys between the asperities serve as reservoirs for solid lubricant materials. The disadvantage of rough surfaces is that sharp asperity peaks can increase run-in wear; however, the surface topography can be controlled to minimize this.

The effect on endurance life of applying molybdenum disulfide (MoS_2) films to surfaces with different roughnesses was shown in Ref. (23). Endurance lives in that study were obtained for MoS_2 films applied to polished, sanded, and sandblasted surfaces. The sanded surface provided up to 20 times, and the sandblasted surface provided up to 400 times, the endurance life of the polished surface.

The second mechanism takes place when a coating (thick film) is employed. For this mechanism to work the coating must be capable of supporting the load. The lubrication process will then involve the shear between a transfer film on the pin and a thin, ordered solid lubricant layer on the coating surface. The wear process is one of gradual wear through the coating. Figure 12 shows actual cross-sectional areas of a polyimide-bonded graphite fluoride film after experiencing a pin sliding over it for various sliding intervals. Note that the vertical magnification is 50 times the horizontal magnification to emphasize the wear process. Initially, the film asperities were capable of supporting the

load, and it could be seen by high-magnification optical microscopy that an extremely thin shear layer had developed on the coating surface. It took 3,500 kilocycles of sliding to wear through this 40- μm -thick coating and reach the metallic surface.

The advantage of this lubrication mechanism is that once the metallic surface is reached by the pin (counterface), continued lubrication can occur by the first mechanism (i.e., shear of a thin film on the metallic surface). Thus, much longer endurance lives are obtainable with coatings. This particular coating had an endurance life of 8,500 kilocycles. Studies have shown that the rate of this particular coating wear was determined by the load and by the contact area of the metallic slider (24). Reducing the contact area or the load extended the endurance life.

One caveat to be aware of in this wear process is that if the coating does not have the strength to support a particular load, it will quickly be worn away (either it will plastically deform or brittlely fracture, debonding from the surface). This result is not necessarily bad because a "secondary film" can form from wear debris and/or material that has not been debonded. However, if the film is too thick or the geometry is not correct, the secondary film may not form at all. Thus, it is important to know how thick to apply a film. A thin film has a better chance of forming a very thin shear film than does a coating (a thick film) that will not support the load. With a thin film there is less chance of wear particles escaping the contact area during

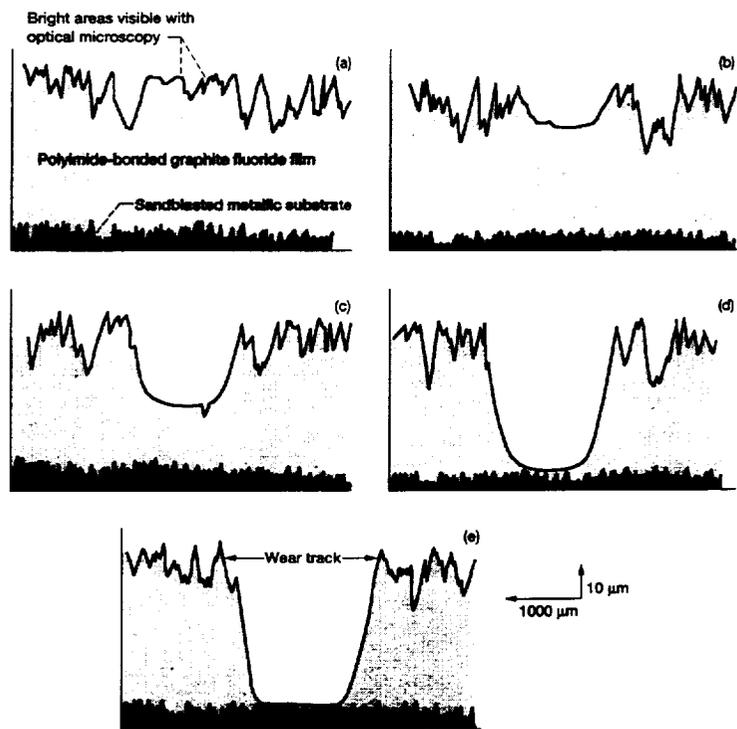


Fig. 12 - Surface wear profiles of a polyimide-bonded graphite fluoride film (which were taken after various sliding intervals for a 0.95-mm-diameter pin flat sliding against the film) illustrating the thick film lubricating mechanism (22).

Advantages	Disadvantages
Long endurance lives if properly employed Low mechanical noise in most lubrication regimes Promotion of thermal conductance between surfaces Very low friction in elastohydrodynamic lubrication regime No wear in hydrodynamic or elastohydrodynamic regimes No wear debris	Finite vapor pressure (oil loss and contamination) Lubrication temperature dependent (viscosity, creep, vapor pressure) Seals or barrier coatings needed to prevent creep Friction (viscous) dependent on speed Endurance life dependent on lubricant degradation or loss Electrically insulating Additives necessary for boundary lubrication regime Long-term storage difficult Accelerated testing difficult if not impossible

Advantages	Disadvantages
Negative vapor pressure (no contamination) Wide operating temperature range No migration of lubricants Good boundary lubrication and electrical conductivity Minimal degradation Accelerated testing possible Good long-term storage No viscosity effects Corrosion protection	Endurance life dependent on operating conditions, e.g., -Atmosphere (air, vacuum, etc.) -Sliding speed -Load and contact geometry Finite life Some wear -Opening up clearances -Producing wear debris Poor thermal characteristics (no heat dissipation) Reapplication difficult or impossible Heavy transfer (can produce erratic torque at low speeds) Inability to be evaluated in air for use in vacuum

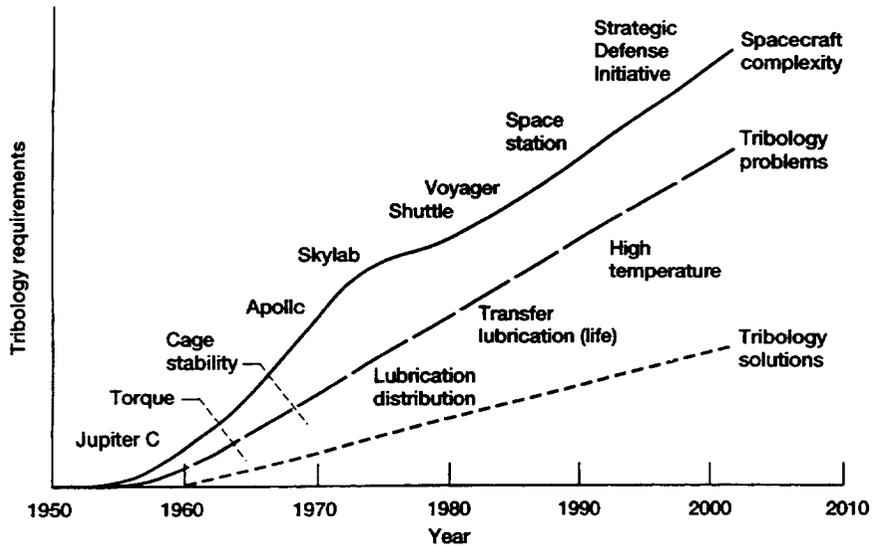


Fig. 13 - Growth of tribology requirements with advances in space (25).

film deformation (known as run-in).

Other Factors Affecting Solid Lubrication

Many factors or conditions also affect solid lubricant performance: type of substrate material onto which a solid lubricant film is deposited, surface finish of substrate material, type of counterface material, surface finish of counterface material, surface to which a solid lubricant film is applied, surface hardness of substrate and counterface materials, geometry of sliding specimens, contact stress or pressure, temperature, sliding speed, and environment (atmosphere, fluids, dirt). Depending on the particular solid lubricant employed, changing the value of just one of these parameters can alter the coefficient of friction, wear rate, or endurance life. Also, a point to remember is that low friction does not necessarily correlate to low wear or long endurance lives. For a more detailed discussion of how these factors affect solid lubricant performance, see (12). One cannot specify a wear rate or a coefficient of friction without knowing all the conditions under which the mechanism will be operating.

Advantages and Disadvantages of Solid and Liquid Lubricants

Some of the various difficulties associated with using solid and liquid lubricants have been discussed in previous sections of this article. Table 2 summarizes the advantages and disadvantages of using liquid lubricants for space applications; and Table 3 summarizes the advantages and disadvantages for using solid lubricants for space applications.

**FUTURE SPACE TRIBOLOGICAL CHALLENGES
Spacecraft**

Kannel and Dufrane (25) conducted a study of the tribological problems that have occurred in the past and are projected to occur in future space missions. Figure 13 (25) is a qualitative chart which illustrates that despite significant advances in tribology, the demands on tribology for future space missions will grow faster than the solutions.

Lubrication problems in space are dependent on the particular application. In many cases, there are no loads on bearings in space and they have to

TABLE 4—REACTION EFFICIENCIES OF SELECTED TRIBOMATERIALS WITH ATOMIC OXYGEN IN LOW EARTH ORBIT (27)	
Material	Reaction efficiency, cm ³ /atom
Kapton	3.0x10 ²⁴
Mylar	3.4
Tedlar	3.2
Polyethylene	3.7
Polysulfone	2.4
1034C graphite/epoxy	2.1
5208/T300 graphite/epoxy	2.6
Epoxy	1.7
Silicones	1.7
PTFE	<.05
Carbon (various forms)	0.9x10 ²⁴ to 1.7x10 ²⁴
Silver	Heavily attacked

be preloaded. Also, many bearings in Earth orbit operate predominantly in the elasto-hydrodynamic lubrication regime. For these reasons the stresses on the oils may not be as great in Earth orbit as they are on the ground. Thus, the lubricants employed have produced fairly good success over the years. However, loss of lubricant through vaporization, creep, and degradation has caused some bearings to fail before their missions were complete.

In an attempt to reduce vaporization (and also contamination) new synthetic lubricants, such as the PFPAE's, have been employed that have extremely low evaporation rates (8). These lubricants also have excellent viscosity characteristics. Although, in theory, these lubricants appear to be exceptional, in operation some failures have occurred from chemical breakdown. Researchers have shown that the presence of chemically active surfaces and/or wear particles combined with exposed radicals in the fluid will inevitably result in acidic breakdown of the lubricants (18-20). More research needs to be done to understand this breakdown process in order to make synthetic lubricants reliable. Another problem with these lubricants is that traditional mineral oil additives are not soluble in them. New additives need to be developed for these PFPAE lubricants.

Solid lubricant films are used where it is not convenient to use liquid lubricants or where contamination might be a problem. As mentioned previously, solid lubricant films have finite lives. As a general rule of thumb they are not employed where they will experience more than 1 million sliding cycles. An additional problem with some solids is that sometimes powdery wear particles can be produced which can pose a contamination problem on sensitive surfaces. There is a need to develop solid lubricant films that will provide longer endurance lives and not produce powdery wear particles.

A significant problem for space lubrication is the lack of oxygen. Oxide layers on metals play an important role in the boundary film lubrication process. On Earth most surfaces are covered with oxide films; these films help to prevent adhesion between surfaces. In a vacuum, if these oxides are removed (by the sliding process), they cannot be reformed as they are on Earth and severe wear of metallic surfaces will occur. This is one reason that boundary additives are necessary in oils; that is, if for some reason metal-to-metal contact occurs and removes an oxide film, the additives can then reform an oxide film or some other type of surface film to prevent future metal-to-metal contact. In the case of nonlubricated sliding or solid lubricant sliding, where oxide films cannot be replaced if worn away, catastrophic failure can occur. Thus, it is important for any metallic surface sliding in a vacuum to be covered with some type of film to prevent metal-to-metal contact.

Atomic oxygen is the major constituent in a low-Earth-orbit environment. NASA has just recently recognized it as being an important consideration in the design of long-lived spacecraft (26). Experiments on two space shuttle missions (STS 5 and 6) as well as with the Long Duration Exposure Facility (LDEF) have shown that material surfaces can change when exposed to atomic oxygen. Carbon, silver, and osmium have been found to react quickly enough to produce macroscopic changes in their structures. Carbon reacts to form volatile oxides. Silver forms heavy oxide layers that eventually flake or spall, resulting in material loss.

Polymers, such as epoxies, polyurethanes, and polyamides, also have been found to be reactive with atomic oxygen. The reaction efficiency did not seem to be strongly dependent on chemical structure, however. Some representative reaction efficiencies are shown in Table 4. The efficiencies are expressed as the volume of material lost per incident oxygen atom. The data indicate that using polymers (either as binders or alone as solid lubricants) may not be appropriate if the polymer is to undergo long exposure to atomic oxygen. Preliminary indications are that atomic oxygen also degrades MoS₂.

Planetary Surface Vehicles and Lunar Processing Plants

It is anticipated that when a manned outpost is established on the Moon, the high vacuum (10⁻¹² torr) combined with the fine abrasive dust will have a deleterious effect on sliding components, especially if they are unlubricated. The dust will accelerate the removal of protective oxide films on metals. This could especially be a problem with "track type" vehicles. In addition to being abrasive, the dust is also positively charged; thus it will have a tendency to adhere to everything. Lubricants, both liquid and solid, will have to be sealed so that the dust cannot invade them. New concepts in sealing will be needed.

Another anticipated problem on the Moon is the wide temperature extremes. In the daytime the temperature can reach 111°C; at night it can fall to -181°C, as was found during the Apollo missions (27). And because the Moon's rotation rate is low, days and nights on the Moon are 14 Earth days long. (By contrast to the lunar temperature, recorded temperature extremes on the surface of the Earth range from -88.3°C in Antarctica in 1960 and to 58.0°C in Libya in 1922 (28). Currently, no liquid lubricants will operate at these cold lunar temperatures. Either the lubricants will have to be heated (which will expend precious

energy) or solids must be employed. Even so, this is an area where little technology research has been performed. Research needs to be conducted to better understand how to lubricate at these low temperatures.

In addition, the Moon has no protective atmosphere to shield mechanical equipment and their tribological systems from solar and cosmic radiation. There is no long-term experience as to how equipment will perform under these conditions.

Space Simulation Problems

Because the tribological properties of materials are extremely system dependent (i.e., the friction, wear, and lubricating ability are strongly dependent on such operating conditions as load, speed, type of contact, temperature, and atmosphere), it is imperative that technology testing simulate as closely as possible the particular space application. The vacuum, load, speeds, etc., can be simulated fairly easily on the ground, but it is not as easy to simulate zero gravity or the radiation/atomic oxygen environment of low Earth orbit.

Also difficult to simulate through technology testing are the forces and vibrations experienced by mechanical components during launch. These parameters can cause a lubricant or component to fail immediately, or they can decrease the life predicted through ground-based testing.

Problems can also occur through storage of satellites. Satellites are sometimes stored for years before launch. Oils tend to creep away from contact zones, solid lubricants can oxidize or absorb water and decrease their lubricating ability, etc. More research needs to be done in these areas to determine which parameters are important and which are not important.

Accelerated Testing Problems

Designers would like to know how long a particular mechanical component will operate before it fails. Presently, the only way to ascertain this is to operate the mechanism in a full-scale ground test. The problem is that these tests may have to run for years. Accelerated testing can be done on some solid lubricants because wear rate is often speed independent. When this is the case, the sliding speed can be simply increased to increase the number of sliding cycles.

Because liquid lubrication is not speed independent, speed cannot be increased to accelerate the test. Therefore, a better understanding of the failure mechanisms of liquid lubricants is needed so that these mechanisms can be analytically modeled to simulate a life test. It may be possible to determine failure precursors on bearings surfaces (such as chemical changes or microcracks) by using surface science. Knowing these precursors would allow us to predict bearing life under various testing conditions and to make corrections that would extend bearing life.

POTENTIAL NEW LUBRICATION TECHNOLOGIES

Dense Thin Films of Solid Lubricants

Sputtered MoS₂ coatings have been used as lubricants for many years (29-30). Recent improvement in sputtering technology by programs conducted at the National Centre of Tribology in the United Kingdom (31) and by programs sponsored by the Strategic Defense Initiative (SDI) (32-

34) have produced dense, thin films of sputtered MoS₂ that have exhibited extremely low friction coefficients (as low as 0.01) and long endurance lives (millions of revolutions in a space bearing). These films show considerable promise for space applications where billions of cycles are not required.

Powder Lubrication

Heshmat (35-36) has been investigating the use of fine powders to lubricate rolling-element and sliding bearings. His studies have indicated that the powders (under certain conditions) flow much like liquids in hydrodynamic lubrication. The results are preliminary, but they suggest the potential for using powders to lubricate at high temperatures where liquids will not function.

Novel Noncontact Lubrication Solutions

An alternative to using oils or solids to lubricate a moving component is to use a high-pressure gas film, either externally pressurized as in a hydrostatic gas bearing or self-acting as in a hydrodynamic foil bearing. Gas bearings have been used for many years. One problem with them is that at start-up or shutdown the sliding surfaces come into contact, so that they have to be hydrostatically elevated or coated with a solid lubricant to lubricate the surfaces during these intervals (37). Also overloads and shock loads can cause high-speed sliding contact, further demonstrating the need for a solid lubricant coating. Gas bearings are somewhat limited in their load-carrying ability, but they work well for high-speed applications.

Magnetic Bearings

Magnetic bearings essentially use opposing magnetic fields to separate the sliding surfaces. Usually, a combination of permanent and electromagnetic materials is used. Magnetic bearings are not widely used today, but they have considerable promise for future lubricating systems (38). One of the problems inhibiting their use has been that complicated and heavy electronic systems are required to ensure their success. With the development of improved electronics in recent years the future use of magnetic bearings appears promising. Solid lubricant coatings must be incorporated into the design of these bearings to prevent wear damage during an occasional bump.

Hard Coatings

In general, hard coatings are not considered to be lubricants, but they do prevent wear and sometimes reduce friction. To date, not many "nonlubricating" coatings have been used in space applications. Miyoshi (39-41) has shown that these materials have considerable promise for use in space systems. The author believes that hard coatings could be used in conjunction with layer lattice solid lubricants to help extend endurance lives. In addition, they might be used with liquid lubricants to reduce friction and wear during boundary lubrication. There are many other potential applications.

In Situ Sputtering of Solid Lubricants

Although it has not been attempted yet, the author suggests that, because many space applications occur in a vacuum, it may be possible to develop sputtering systems

that could sputter a solid lubricant material onto a surface while it is in operation. This would be one way of resupplying solid lubricant films and essentially providing infinite endurance life.

CONCLUDING REMARKS

This article has presented an overview of the current state-of-the-art tribology, some current and future perceived space lubrication problem areas, and some potential new lubrication technologies. It is the author's opinion that tribology technology, in general, has not significantly advanced over the last 20 to 30 years, even though some incremental improvements in the technology have occurred. There is a better understanding of elastohydrodynamic lubrication, some new lubricating and wear theories have been developed, and some new liquid and solid lubricants have been formulated. However, the important problems of being able to lubricate reliably at high temperatures or at cryogenic temperatures have not been adequately addressed.

The need is even greater in the area of space tribology: little new lubrication technology has been developed for use in space since the Apollo years. The same technology is still being used today, 20 years later. The technology has worked adequately for most NASA missions that have flown to date; but as NASA plans longer duration, more demanding missions, the technology will not be sufficient.

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